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Published in:
Volcanic Degassing: Geological Society, Special Publication 213

Publication date:
2003

Citation for published version (APA):
Taylor, S., Durand, M., & Grattan, J. (2003). Illness and elevated Human Mortality in Europe Coincident with the Laki Fissure eruption. In *Volcanic Degassing: Geological Society, Special Publication 213* (pp. 410-414). Geological Society of London. http://hdl.handle.net/2160/230

Illness and Elevated Human Mortality in Europe Coincident with the Laki Fissure Eruption

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Abstract: Volcanic eruptions represent a significant source of volatile gases that are harmful to human health. This chapter reviews and develops current understanding of the human health response to volcanogenic pollution and dry fog events; in particular it explores the health impact of the gases from the Laki fissure eruption, and presents data that point to a significant increase in the national death rate in England coincident with the early phases of the eruption. It is noted that many common symptoms of severe exposure to air pollution can be linked to the dry fog of 1783; these included difficulty in breathing, eye and skin irritation, headaches, loss of appetite and tiredness.

> Such multitudes are indisposed by fevers in this country, that farmers have with difficulty gathered in their harvest, the labourers having been almost every day carried out of the field incapable of work and many die.
>
> (Cowper Letters, 1783)

Introduction

The Laki fissure eruption is notorious for its devastating impact upon the ecology of Iceland and the death of *c.*25% of the island's human population in the eruption's aftermath, the result of induced illness, subsequent environmental stress and famine (Thórarinsson 1979, 1981; Steingrimsson, 1998). The eruption has been the subject of extensive research, not only for its atmospheric effects but also because investigations of 18th-century written sources now confirm that profound health and environmental impacts occurred throughout Europe and beyond (Grattan & Charman 1994; Grattan & Pyatt 1994, 1999; Grattan & Brayshay 1995; Stothers 1996; Demarée *et al.* 1998; Jacoby *et al.* 1999; Durand & Grattan 1999; Grattan 1998; Grattan *et al.* 1998; Brayshay & Grattan 1999; Dodgshon *et al.* 2000; Durand 2000; Thordarson & Self 2001).

As a recent historical event it is possible to study the impact of the eruption across a wide range of human activity by tracing the written records left by contemporary observers during the eruption period and through detailed summaries written in the years immediately following. Other documentary sources, such as parish burial records, where available, may also yield valuable information. This chapter explores the material evidence for the impact of the 1783 dry fog upon human health and mortality, and suggests that certain features of English death rates during the year point to an episode of crisis mortality, where mortality was greater than 10% in excess of the moving 51-year mean (Wrigley & Schofield 1989). This chapter discusses the intriguing possibility that in England the environmental forcing associated with the eruption may have lead to a marked increase in the death rate in the summer of 1783.

Air pollution and volcanic eruptions

The scale of the air pollution generated by the Laki fissure eruption in terms of geographical extent and duration dwarfs any reported natural or anthropogenic event, including the recent smogs generated by the burning of the Indonesian rainforests and peats (Khandekar *et al.* 2000). It is now widely accepted that volcanic eruptions may affect distant environments via a number of mechanisms. In addition to climate cooling, which has been the focus of much research, recent work has investigated the association of volcanic gases with high surface air temperatures (Wood 1984, 1992; Grattan & Sadler 1999, 2001)

From: OPPENHEIMER, C., PYLE, D.M. & BARCLAY, J. (eds) *Volcanic Degassing*. Geological Society, London, Special Publications, **213**, 401–414. 0305–8719/03/$15.00

and large-scale air-pollution events or dry fogs (Grattan & Charman 1994; Grattan & Brayshay 1995; Jacoby *et al.* 1999; Thordarson 1995; Demarée *et al*. 1998; Grattan 1998; Grattan *et al.* 1998). Many of the gases emitted by volcanoes are similar to those emitted from anthropogenic sources, and the toxicological and epidemiological properties of the latter have been widely studied (Wellburn 1994; Pope *et al*. 1995). Physiological and chemical evidence substantiates the importance of SO_2, H_2SO_4, H_2S, HCl, HF, NH_3 and sub-PM_{10} particles as toxic air pollutants, most of which are commonly emitted during volcanic activity.

Research into the impacts of volcanic gas upon human health and the environment has typically focused upon populations and environments relatively close to the volcano. Symptoms of moderate exposure of this type include skin, eye, and digestive irritation and respiratory problems, while fluorosis, bone damage, coma and even death are among the more severe problems that may be encountered in relative proximity to the volcanic vent (Thórarinsson 1979; Baxter *et al*. 1982, 1990; Hickling *et al*. 1999; Allen *et al*. 2000; Delmelle *et al*. 2001). High gas concentrations and pollution-related illnesses and fatalities have been noted at considerable distances downwind from active volcanoes following atmospheric transport of a volcanic plume. In many of the known cases of volcanogenic air-pollution, damage to vegetation and human physiological responses to the pollution have occurred (Thórarinsson 1979, 1981; Baxter *et al*. 1982). A notable modern example of this is in the region of Masaya volcano, Nicaragua. During the peak in its *c.*25-year activity cycle, Masaya emits up to 1300 t /day SO_2, 400 t/day HCl and 5 t/day HF (Baxter *et al*. 1982). Baxter *et al*. (1982) suggested that people exposed to the plume downwind from the volcano could regularly be exposed to SO_2 at concentrations above 1 ppm, or 20 times the World Health Organisation 24-h exposure limit of 100–150 $\mu g/m^3$. Durand (2000) modelled the trajectory of the Stromboli volcanic plume around the Mediterranean and demonstrated that it may maintain its integrity over trajectories of considerable distances, to cities in Italy, Greece and North Africa, where it may contribute to ongoing anthropogenic air-pollution problems.

Air pollution and mortality

The concept that severe anthropogenic air pollution may cause respiratory illness and/or the death of vulnerable sections of the population is familiar in modern societies. Studies which have analysed mortality data from famous air-pollution events, such as that in London in 1952 (Wilkins 1954), the Meuse Valley in Belgium in 1930 (Firket 1936) and Donora, Pennsylvania, USA, in 1948 (Shrenk *et al*. 1949), have suggested that concentrations of SO_2 and levels of acidity were the primary cause of excess mortality. Subsequently, a large number of studies have reported statistical associations between air pollution and excess mortality (Mazumdar *et al*. 1982; Ostro 1984, 1993; Lippmann 1989; Fairly 1990; Schwartz & Marcus 1990; Ostro *et al*. 1991, 1993; Schwartz 1991; Dockery *et al*. 1992; Pope *et al*. 1992, 1995; Ito *et al*. 1993, Pope & Kanner 1993). There are no compelling reasons to propose that volcanogenic air pollution, of sufficient concentration, may not have a similar impact on human health to anthropogenic air pollution, and Stothers (1999, 2000) has already pointed to a clear relationship between significant volcanic eruptions, dry fogs and pandemics of considerable magnitude.

The pollution impacts of the Laki fissure eruption

Stothers (1996) suggested the total mass of aerosols produced by the erupted gases may have approached 200 Mt, while Thordarson and Self (2001) estimated that during June–July 1783 up to 6 Mt of acid aerosol was added to the European air mass each day, and that the concentration of the sulphuric acid aerosol in the boundary layer of the atmosphere may have exceeded several tens of mg/L; concentrations which are easily capable of causing a severe physiological reaction.

Eruption dynamics

The dynamics of the Laki fissure eruption are covered in great detail in a series of research papers (cf. Thordarson & Self 1993; Thordarson *et al*. 1995) and are only covered very generally here. In brief, the fissure eruption took place between June 1783 and February 1784 and emitted approximately 120 Mt SO_2, 6.8 Mt HCl and 15.1 Mt HF plus H_2S and NH_3, with peak emissions during June and July 1783, with the majority of emissions confined to the troposphere (Thordarson & Self 1993, 2001; Thordarson *et al*. 1996; Sparks *et al*. 1997).

Meteorology

A series of high-pressure air masses were positioned over northwest Europe throughout the summer of 1783 (Kington 1988). Several researchers (Grattan & Brayshay 1995; Thordarson & Self 2001) have proposed simple atmospheric circulation models which could account for the transport of significant quantities of volcanogenic volatiles from Iceland to the boundary layer of the atmosphere over the British Isles and Europe. This meteorological situation resulted in the concentration of eruptive gases, which were manifested as a persistent, foul-smelling dry fog, which was reported across Europe (Grattan & Pyatt 1994; Stothers 1996).

The presence of stable air masses in the European summer is usually associated with fine weather and high surface temperatures, and the summer of 1783 was no exception. What was exceptional about the summer of 1783 were the temperatures reached. The July of 1783 was one of the hottest ever recorded in Europe; while in England, with a mean daily temperature of 18.8°C, it was the hottest month recorded in Manley's (1974) 'Central England Temperature Record'. It has been suggested that these high temperatures were caused by the adsorption and retention of thermal energy by the dry fog (Grattan & Sadler 1999, 2001), which is in striking contrast to the emphasis given to climatic cooling in much other research.

Pollution damage to vegetation

Irrefutable evidence of the toxic nature of the dry fog beyond Iceland may be drawn from the numerous descriptions of acid damage to crops, trees and other plants which may be found in Britain, Norway, Sweden, The Netherlands, France, Germany and Italy (Table 1). Collectively, the available data suggest that on occasions the pH of the dry fog frequently fell below pH 2, and that as well as sulphur it contained

Table 1. *Summary of documentary accounts of acid damage to vegetation in 1783.*

Location	Observed weather	Summary of symptoms of damage	Source
England	'Uncommon gloom', smoky fog	Cereal crops: yellowed Barley: withered awns Oats: withered Rye: mildewed in appearance Beans: whitened & dying Pasture: dried Trees: shedding leaves and appear scorched as if by fire	Cullum (Grattan & Charman 1994) *Ipswich Journal*, 12 July 1783 *Cambridge Chronicle and Journal*, 5 July 1783 *Sherbourne Mercury*, 14 July 1783
France	Sulphurous dry fog	Vine flowers: burned Olives: fruit burned and falling Peas: badly damaged Marrows: badly damaged Melons: badly damaged Tree leaves: damaged Damaged the corn, which yielded hardly any crop	Rabartin & Rocher (1993)
Italy	Dry fog	Damaged wheat, empty ears, dried ears.	Camuffo & Enzi (1995)
Netherlands	Persistent 'strong' fog with a sulphurous smell.	Leaves of bean and pear trees 'affected' 'Changes to plants' Bleached leaves. Leaf and fruit fall Drying and bleaching of leaves, some developing spots Leaf fall	Swinden (1786, 2001) Brugmans (1787)
Norway	Smoky fog, 'Acrid rain'	Withered vegetation. Tree leaves 'partly burnt' Grass blackened	Thórarinsson (1981)
Sweden	Smoky fog	Crops destroyed; very poor harvest	Thórarinsson (1981)

fluorine, of which 8 Mt are thought to have been released to the atmosphere during the eruption (Thordarson *et al*. 1996).

Human illness in the summer of 1783

Accounts from England, France, Italy and Scandinavia confidently associate the dry fog, associated meteorology and other environmental changes with a variety of illnesses and even death. Contemporary descriptions of human ill-health in 1783 are remarkably consistent, and link the dry fog, or a strong sulphurous stench, with headaches, eye irritation, decreased lung function, and asthma, which are consistent with the expected health impacts of the suite of gases emitted. The health symptoms described point to considerable concentrations of volcanic gases and derived aerosols (Table 2). Modern research outlined above suggests that the health risk presented by volcanic air pollutants and sustained dry fogs may be significant.

The currently available literature describing the human health impacts of the 1783 dry fog have been reviewed in comprehensive detail elsewhere (cf. Durand & Grattan 1999; Thordarson & Self 2001, and references therein) and are summarized in Table 2. For an accessible translation of one of the most detailed eyewitness accounts of the impact of the dry fog in The Netherlands, the reader is referred to a recently published translation (Swinden 2001). However, a flavour of the times can be gained from the following passage, also written in The Netherlands:

> After the 24th (of June), many people in the open air experienced an uncomfortable pressure, headaches and experienced a difficulty breathing exactly like that encountered when the air is full of burning sulphur … asthmatics suffered to an even greater degree. (Brugmans 1787)

Where the symptoms of illness described are clear rather than general, it is possible to propose air pollution as a potential cause (Table 2). In particular, within the available data it is clear that respiratory problems were commonly associated with the dry fog, a physiological response that is typical of modern air-pollution incidents, particularly where SO_2 is present at concentrations greater than 570 μgm^3 (Dassen *et al*. 1986; Brunekreef *et al*. 1991; Dockery *et al*. 1992; Wellburn 1994; Beverland 1998).

In addition to the respiratory and cardiovascular health impacts associated with the volcanic gases, which are reported in the summer of 1783, it is necessary to consider other potential sources of illness associated with another major environmental factor present in the summer of 1783, the record high daily temperatures. Commentaries frequently discuss the distress felt by many at the ‘intolerable heat’. One might reasonably suppose that the heat could have had an effect on water quality and thus enteric sickness, but as yet the specific symptoms described point to illness induced by air pollution rather than illness caused by bacteria and viruses. General comments, however, do make reference to fevers, epidemics and mortality of

Table 2. *Summary of human symptoms and possible causes in 1783. Suggestions for possible gases and their ambient concentrations required to induce the symptoms, as inferred from the historical literature, are given.*

Condition reported in the original literature	Gas	Exposure required	Possible explanation
‘Disagreeable’ symptoms and ‘sensations’ in chests	SO_2	>80 μg/m^3	Bronchitis worsened
	SO_2	>572 μg/m^3	Asthma worsened
‘Pestilence’ and ‘tingling’ of the throat	SO_2		Bronchitis induced (especially in those predisposed to asthma)
Headache	H_2S	<10 ppm	Headaches induced
	F (p)		
‘Tingling’ and ‘tired’ eyes	H_2S	14.2–28.4 μg/m^3	Eye irritation threshold
		28.4–70.9 μg/m^3	Severe eye irritation and impairment
		70.9 μg/m^3	Eye damage
	SO_2	800 μg/m^3	Eye irritation occurs (concentration required is lower if other irritants or particulates are involved)
Loss of appetite	H_2S	<10 ppm	

Dosimetry data are from Wellburn (1994) and Beverland (1998).

which the following, from England are typical:

> Letters from various parts agree that the season is very unhealthy; the lower order of people in the country have felt its effects severely. A fever rages in many parts, which the people term the Black Fever.
>
> (Gilpin 1763–1785).

> The epidemic begins to be more mortal as the autumn comes on . . . and in Bedfordshire it is reported . . . to be nearly as fatal as the plague. . . . This light atmosphere and these unremitting storms are very unfriendly to an asthmatic habit.
>
> (Cowper correspondence, 8 September 1783).

In addition to illnesses, contemporary observers were quick to associate the dry fog with unusual patterns of mortality, as noted below in France, Italy and England.

> A phenomenon of prolonged and very dense fog, which completely hid the sun, and at night made the moon appear reddish and murky. This fog caused, moreover, many illnesses and putrid and acute fevers, so that many people died.
>
> (Fajonio, cited in Camuffo & Enzi 1995)

> The fogs have been followed by great storms and sicknesses which have driven a third of the men in many parishes to their tombs.
>
> (The Curé of Landelles, cited in Rabartin & Rocher 1993)

> While the sun was obscured there was a sickness, which caused innumerable deaths'.
>
> (The Curé of Broué, cited in Rabartin & Rocher 1993)

> Such multitudes are indisposed by fevers in this country, that farmers have with difficulty gathered in their harvest, the labourers having been almost every day carried out of the field incapable of work and many die.
>
> (Cowper correspondence, 7 September 1783)

The available qualitative data all point to human illness and mortality in the summer of 1783, phenomena that were clearly associated in the minds of the observers with the state of the atmosphere; below some quantitative data for this period are explored.

English mortality trends in 1783–1784

Methodology

English mortality trends at the national level have been explored by consulting the data published in the 'Population History of England' (Wrigley & Schofield 1989). At the level of individual parishes the 'Population History of England Database' (Schofield 1998) has been used; the quality of these data has been comprehensively verified. Mortality indices have been calculated for these data, following the procedures laid down in Dobson (1987, 1997).

Annual trends

In studies of the population history of England (Dobson 1987, 1997; Wrigley & Schofield 1989) the period July 1783 – June 1784 is recognized as containing a one-star mortality crisis, indicating an annual mortality rate 10–20% above the 51-year moving mean; which qualitatively describes the state of the nation's health in the period as 'unhealthy'. In fact the national death rate for 1783–1784 has been calculated to have been 16.7% above the projected trend for this period. In a world where clean water, sanitation and food hygiene were rarely prioritized, and where epidemic disease was common and infectious disease rife, mortality crises were not unusual. Twenty-two three- and two-star mortality crises (mortality that was 20–30% greater than the National Crude Death Rate; cf. Dobson 1997, p. 383) are listed by Wrigley and Schofield (1989), for the period 1541–1870; all of these were nationally more severe than the mortality evident in the annual death rate for 1783–1784. This period, therefore, while an acknowledged mortality crisis, is only one of many apparent in the annual national statistics. However, considering these data at a national level and in annual trends obscures the severity of the mortality experienced in different parishes across the country at this time, and its unusual seasonal pattern.

Seasonality of mortality

Even death has its season – in historical times, in the absence of epidemics, burials normally fell into predictable patterns, which reflect the periods of maximum environmental stress in any region or country. In European historical datasets, in the absence of a forcing factor such as disease, peak mortality usually occurs in March–April, with a trough expected in the summer and early autumn, given better weather and an adequate harvest (Wrigley & Schofield 1989). The national crisis apparent in the annual burial rates for 1783–1784 in England, is largely generated by an unusually high number of burials in the summer (July–September) of 1783. Using the 'Population History of England Database' (Schofield 1998) the anomalous nature of the deaths in the summer of 1783 can be explored. Dobson (1987) proposed the calculation of mortality indices (recorded burials divided by the 51-year moving average and multiplied by 100). The resulting indices are then classified as follows: 200–140 = crisis mortality, 140–120 = high mortality, 120–110 = unhealthy, 110–90 = average, 90–80 = healthy. In Figure 2 these indices have been calculated for the last thirty years of the 18th century. The summer burial rate in 1783 was the highest recorded in the entire 18th century, slightly higher than the burial rate recorded in the summer of 1728, when there was a national epidemic of typhus and smallpox (Figure 1). In 1783 the July–September burials totalled 56 089, as against a truncated 51-year mean of 33 159, and the mortality index assigned to the summer of 1783 is 169 (Table 3), which is indicative of crisis mortality at this time. However, while the mortality crises of the late 1720s are associated with recorded epidemics, the crisis of 1783 remains unexplained in the population histories. The burial rate recorded in the summer of 1783 is clearly defined as a crisis, and falls into the highest category of event.

Monthly mortality

Cowper (cited above) suggested that the 'epidemic' worsened as the summer progressed, and this trend is indeed apparent in the national data (Table 3). July deaths were near normal, and mortality for the month can be classified as entirely average. The summer crisis is mainly the result of the burials that occurred in August and September, with the crisis clearly worsening into September, which is assigned a mortality index of 158, placing it in the highest category of event (Table 3). These monthly data confirm that a severe crisis did occur in the summer of 1783. The calculated means for the summer months are very similar, and death rates through this period were usually low and stable, but this is clearly not the case in 1783, when it is reasonable to assume that an environmental forcing mechanism or disease vector must have been present; the environmental stresses introduced by the Laki fissure may be considered to be a plausible candidate for this event, indeed this is currently the only identified extraneous feature of this period.

Local mortality crises

The data discussed above may be refined further. As discussed in Appendix 10 of 'The Population History of England' (Wrigley & Schofield 1989), the data which point to national trends may in fact be generated by modest increases across the entire country or by a severe fluctuation in a limited number of parishes, the latter being defined as a 'local mortality crisis'. Crisis mortality in just 13.1% of the parishes in the 'Population History of England Database' generated the national and seasonal increase noted

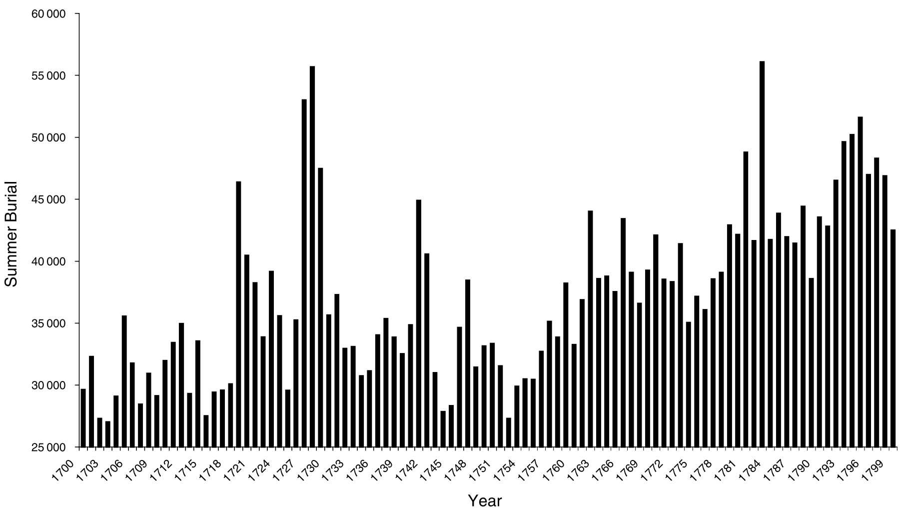


Fig. 1. Eighteenth century English summer burial record.

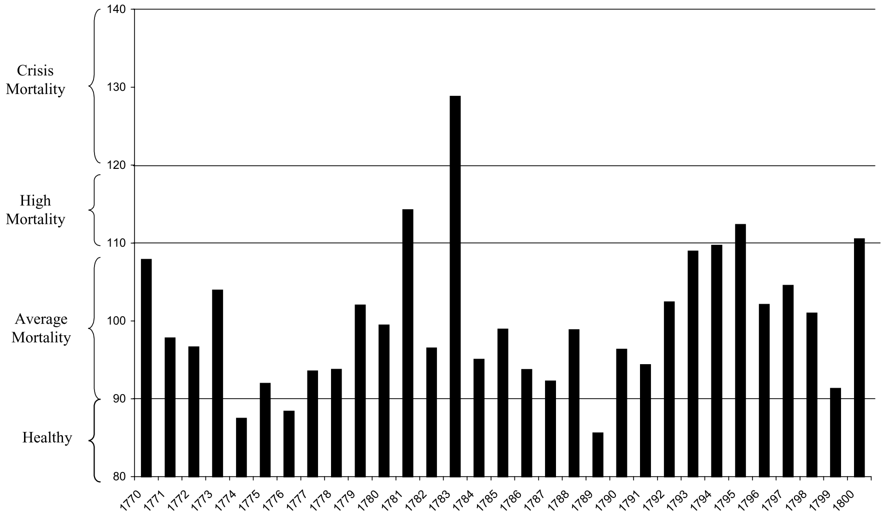


Fig. 2. Mortality indices calculated for English summer burial rates, 1770–1800.

Table 3. *Summary of national mortality statistics*

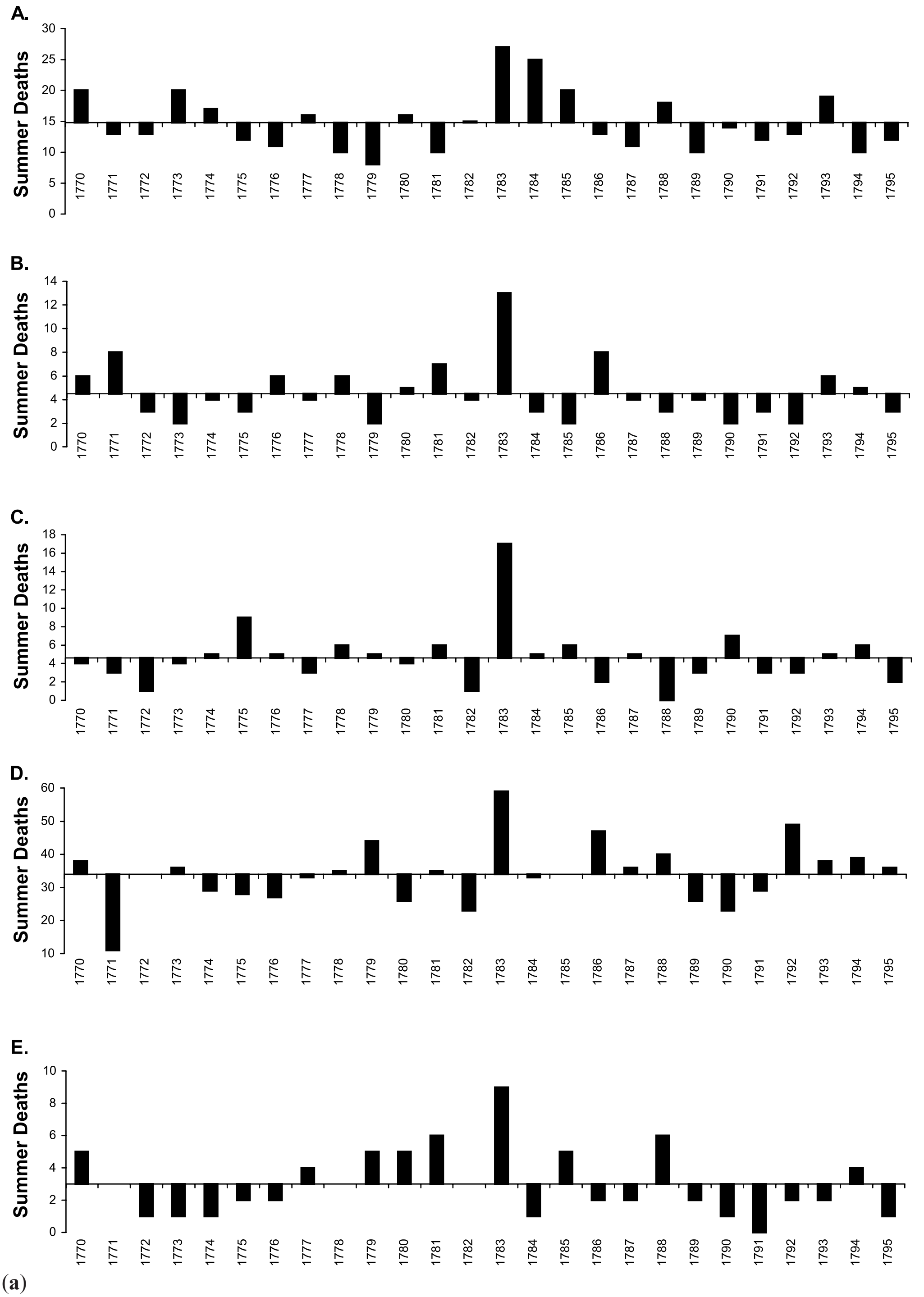
	July–Sept	July	August	September
Total deaths	56 089	15 000	18 338	22 751
Truncated 51-year mean	33 159	14 747	14 429	14 372
Mortality index	169	101	127	158
Mortality classification	Crisis	Average	Unhealthy	Crisis

above (Wrigley & Schofield 1989, pp. 645–694), and the pattern of mortality evident at this time typifies a local mortality crisis. How was this event manifested in the affected parishes? To interrogate the parish mortality data (Schofield 1998), seasonal totals have been calculated by summing the burial figures for each parish for the months July–September. As is typical of local mortality crises, the affected parishes are quite dispersed, with the clearest regional concentrations found in Bedfordshire and East Anglia, while parishes in Gloucestershire, Lincolnshire, and Leicestershire also feature prominently. Ten parishes have been chosen at random from those affected and are presented here (Figs 3a & b). All ten display the unusual mortality pattern typical of those affected in the summer of 1783: excess deaths in the summer months, which are commonly three or more standard deviations from the 1770–1795 mean. In each parish illustrated, it can be seen that the mortality figures for the summer of 1783 are anomalous when compared with the trends over a twenty-five year period, but the data are nonetheless strikingly similar in respect of the deaths, which occurred in 1783.

In a letter written on 8 September 1783, in the midst of this crisis, Cowper specifically commented on the news of the mortality in Bedfordshire, where it was reported to be ‘nearly as fatal as the plague’. The population history database (Schofield 1998), contains records for 28 Bedfordshire parishes; of these, thirteen experienced crisis mortality in the summer of 1783 (Table 4). The reality in people’s lives behind the data presented in Table 4, and the anxiety that these unseasonable deaths must have generated, readily explains Cowper’s comments.

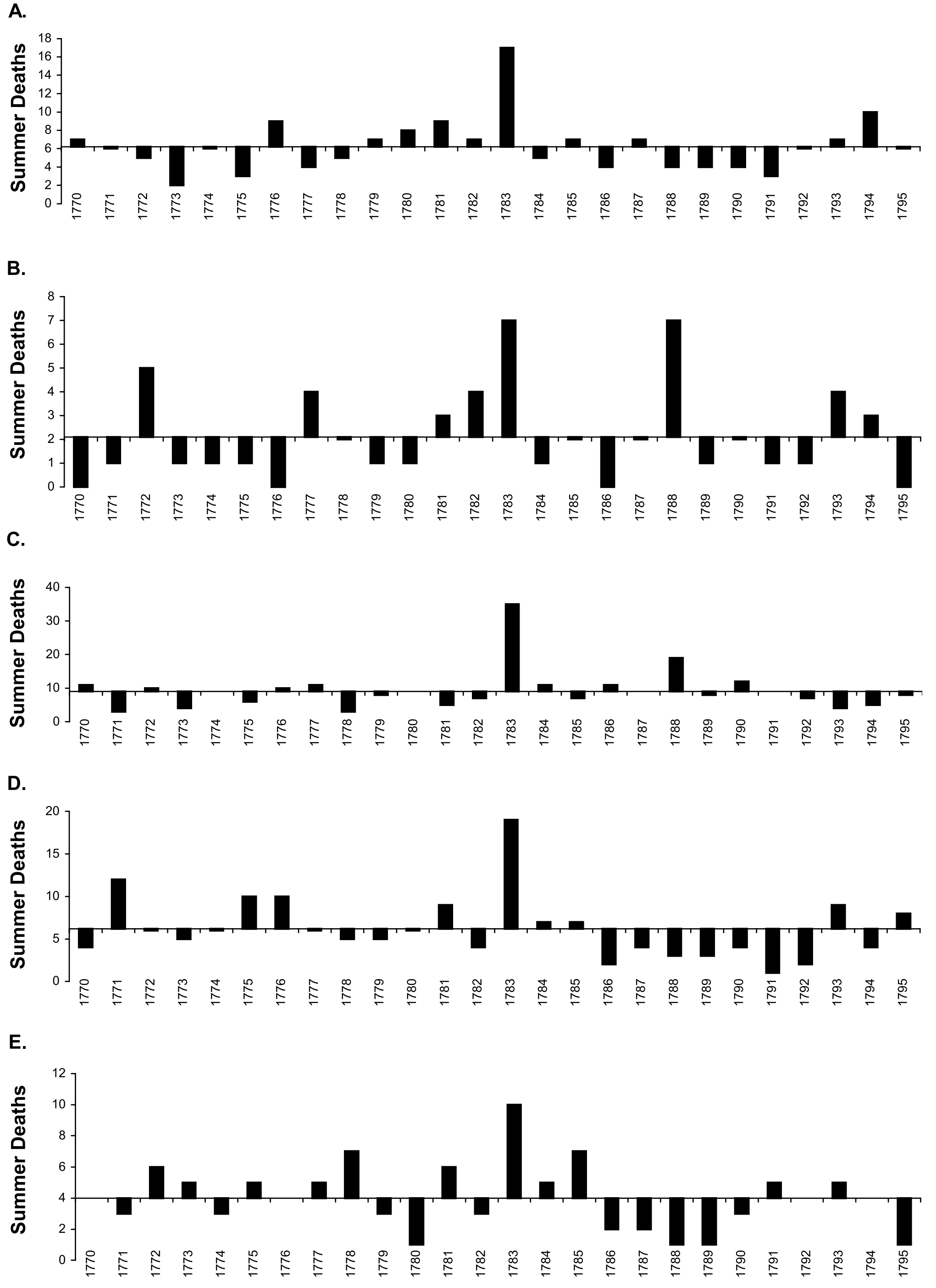
Summary

Taken together, this consideration of mortality data at the national, annual, seasonal, monthly, regional, and parish levels all point to the



(**a**)

Fig. 3 (**a**) Summer mortality, 1770–1795. A, Minchinhampton, Gloucestershire; B, Wye, Kent; C, Great Grimsby, Lincolnshire; D, Edmonton, Middlesex.; E, Blunham, Bedfordshire.



(b)

Fig. 3. (continued) (**b**) Summer mortality, 1770–1795. A, Banham, Norfolk; B, Sculthorpe, Norfolk; C, Castle Donington, Leicestershire; D, Cavendish, Suffolk, E, Fressingfield, Suffolk.

Table 4. *Summer 1783 mortality characteristics for twelve Bedfordshire parishes.*

	Ampthill	Blunham	Clophill	Cranfield	Flitwick	Kempston	Maulden
Total deaths	11	9	8	23	5	12	17
Truncated 51-year mean	5	3	3.6	6	1.5	5.4	5
Mortality Index	217	310	220	365	327	220	354
Mortality classification	Crisis	Crisis	Crisis	Crisis	Crisis	Crisis	Crisis
	Millbrook	Northill	Pavenham	Sandy	Studham	Wooton	
Total deaths	8	6	10	15	6	6	
Truncated 51-year mean	2	3	2	6.5	2	3	
Mortality Index	400	190	467	228	286	190	
Mortality classification	Crisis	Crisis	Crisis	Crisis	Crisis	Crisis	

occurrence of a mortality crisis, which appears more acute as the focus of analysis is refined. Most other mortality events of this type in the population histories are associated with an environmental factor that may account for the anomalous burial rates. Current knowledge identifies the Laki fissure eruption as the major environmental forcing mechanism at this time. The association of these events will be discussed below.

Discussion

The events of the summer of 1783 appear to fall into a growing body of modern work which points to a clear link between air pollution, the ambient environment and mortality. Elsewhere in Europe, data-sets have not yet been collated so extensively. However, Wrigley and Schofield (1989) noted that while mortality crises in one European country were rarely shared by others, the period 1783–1784 is notable for mortality crises in northern Holland and Brabant. Sutherland (1981) has also noted a distinct mortality crisis in Brittany over the same period and Rabartin (pers. comm.) has suggested that the regions of Eure and Loire in central France appear to exhibit a similar pattern of crisis mortality.

Regardless of the cause of this phenomenon, the data presented above illustrate the serious nature of the mortality events occurring in widely separated areas of England, and perhaps elsewhere, in the summer of 1783, and deepen current understanding of a mortality event which has previously only been visible in annual data-sets and regional studies (Wrigley & Schofield 1989; Dobson 1997). The severity of the summer mortality, and the fact that anomalous mortality in a relatively small number of parishes was large enough to influence the national trends, implicates an external forcing factor. The burial rate in the summer of 1783 was higher than the mortality reported during the typhoid and smallpox epidemics of the late 1720s, and it is reasonable to propose that the mechanism responsible for the death rates reported at this time must have been at least as severe. The Laki fissure eruption had a profound impact upon the English and European environment. It generated air pollution on a continental scale, of sufficient concentration to blight many areas of the countryside (Table 1), and induced a range of illnesses that we might expect to see during any modern air-pollution incident (Table 2). In addition to these direct impacts, the gases and aerosols quite probably are responsible for generating some of the hottest weather recorded in England (Manley 1974; Grattan & Sadler 1999), and this may have led to the contamination of vulnerable water supplies.

The degree of the physiological reaction to an environmental stress depends upon an individual's sensitivity and the prevalent micrometeorological conditions, in addition to the strength and duration of exposure. Sensitivity can also be affected by natural physiological differences, including age and sex, as well as socio-economic and life-style factors, in addition to the influence of pre-existing ailments (Goldberg, 1996). Modern studies of anthropogenic air-pollution incidents in and around major cities suggest that in addition to respiratory disorders, similar to those described above, death rates may rise as vulnerable groups are affected by severe air pollution. Elsom (1993) listed five features that are characteristic of a severe air-pollution incident: (1) damage to vegetation, (2) damage to animals, (3) damage to metals and painted surfaces, (4) damage to buildings, (5) weather changes, including reduced visibility and temperature increases. Observers of the dry fog and its impact noted all of these, on the European mainland and Britain in the summer of 1783. Where these factors are present, human illness is normally expected. The health effects of pollutants at the concentrations typical of severe air pollution are necessarily conditioned by the physiological conditions of individuals, but it is expected that a proportion of the individuals in an exposed population will be intolerant of the extra physiological stress and may die (Shy & Finklea 1979). In the context of the environmental variables which may have been present in 1783, high concentrations of sulphur dioxide and high surface air temperatures, it is interesting to note in particular the work of Katsouyanni *et al.* (1993). This study, based on deaths reported in Athens over seven years, noted that while any impact of air pollution alone was not statistically significant, high indices of air pollution in combination with high temperatures were associated with an extra 40 deaths a day in Athens, a relationship which was significant at the $p < 0.5$ significance level. A synergistic relationship between the two variables was proposed, in particular that the high temperatures induced physiological stress, which in turn lowered the thresholds at which the health impacts of air pollution became notable. Touloumi *et al.* (1994) also noted a clear relationship between air pollution and mortality in Athens. Lippmann and Thurston (1996) established positive regression coefficients for health and morbidity with sulphate, and fine suspended particulate material ($PM_{2.5}$–PM_{10}). These observations were broadly confirmed by Vigotti *et al.* (1996), who studied deaths and hospital admissions in conjunction with sulphur dioxide and total suspended particulates in Milan, Italy, in the period 1980–1989. Wichmann and Heinrich (1995) also reported increased mortality and the reported incidence of bronchial illness in association with high concentrations of sulphur dioxide in East Germany; again the similarity with the experience of Europe in 1783 is obvious. The critical factors reported in all these studies, several species of sulphur, suspended particulate material and high air temperatures are all present in the summer of 1783, and it is therefore reasonable to propose that the localized episodes of crisis mortality noted in this period may be also associated with these environmental factors.

It is clear therefore that in many respects the events of the summer of 1783 conform to the patterns established by the study of modern events of shorter duration. These are important factors to consider when the distribution of anomalous mortality in 18th-century England is considered. It is clear from the literature that the intensity of the aerosol impact varied considerably and was dependent on micro-meteorological and topographic features (Grattan & Charman 1994).

If it is accepted, as seems likely from modern air-pollution analogues, that all the anomalous environmental phenomena observed in the summer of 1783 are linked to the emission of gases from the Laki fissure eruption, then a plausible hypothesis can be constructed. Concentrations of SO_2 within the dry fog passed critical thresholds for human health on many occasions, and were clearly responsible for severe respiratory dysfunction in many people and concentrations of SO_2 may therefore have reached 1000 mg/m^3 for long periods of time. However, pre-existing health conditions may be worsened at much lower gas concentrations. Although based on inferences drawn from qualitative data, it can be stated with some confidence that the 1783 dry fog, of several weeks' duration, approached the concentrations of the 1952 London smog (which killed 4000 people), and exceeded the concentrations reached in other notorious air-pollution events such as the Ruhr smog of 1987 (Elsom 1993). Gilpin and Cowper both commented on the distress of agricultural labourers working in the fields, and it has been noted that increased physical activity, which leads to a greater ventilation rate, may increase the exposure of individuals to pollutants in the air (Lawther *et al.* 1975). The high air temperatures may also have intensified the physiological impacts of the pollutants present in the dry fog (Matzarakis & Mayer 1991; Katsouyanni, *et al.* 1993; Mackenbach *et al.* 1993).

It is clear that in many respects the events of 1783 are typical of modern severe air-pollution events, and, in addition, all the contemporary accounts of illness reported in the summer months of 1783 point to air pollution. However, uncertainty does surround the time lag in the data. Modern events impact upon mortality very quickly, whereas in 1783 the excess deaths occurred over a much longer period. It may be that in modern events the precursor conditions are worse and human sensitivity greater than in 1783, but this will necessarily be the focus of further research. However, our current knowledge of the environmental processes active at this time and the abundant qualitative and quantitative data available suggest that acid volcanic gases were the key agent in the events of 1783.

Conclusion

A persistent and intense concentration of volcanic gases from Laki in the atmosphere of the British Isles and Europe during the summer of 1783 has been demonstrated by considerable scholarship, and is no longer in doubt. Direct environmental forcing is clearly apparent in two areas: firstly the numerous descriptions of acid gases and aerosols and their impact upon plants and upon human health, and secondly the extremely high surface air temperatures recorded (Thórarinsson 1979, 1981; Grattan & Charman, 1994; Camuffo & Enzi 1995; Thordarson *et al*. 1996; Stothers 1996; Grattan *et al*. 1998; Durand & Grattan 1999; Durand 2000, Swinden 2001). Contemporary writers were quite clear in their association of all these factors: the sulphurous dry fog, the high temperatures, the damaged vegetation, human sickness and death. Many writers also commented on the distress caused by the extreme heat. All of these factors have been observed to operate synergistically in modern air-pollution events, and there are no compelling reasons why this may not have happened during the continental-scale events of 1783 (Mayer 1990; Matzarakis & Mayer 1991).

This chapter has demonstrated that a notable mortality crisis coincided with a major volcanic eruption, and established that reasonable grounds exist to associate the two events with some confidence. In many areas of the world, air pollution is a serious problem – one need only consider the proximity of many rapidly growing cities and volcanic centres to conclude that, regardless of the events of 1783, volcanic gases will inevitably wield a profound influence upon human health in the future (Durand & Grattan, 2001).

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